TITLE OF THE INVENTION

BALANCED AMPLIFIER AND FILTER USING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the
benefit of priority from the prior Japanese Patent
Applications No. 2001-331805, filed October 30, 2001;
and No. 2002-090388, filed March 28, 2002, the entire
contents of both of which are incorporated herein by
reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a balanced
amplifier and a filter using the same and, more
particularly, to a balanced amplifier whose maximum
value of an output signal amplitude is larger than that
of a conventional amplifier even at a low voltage, and
a filter using the same.

2. Description of the Related Art

A balanced amplifier has a gain only for the
differential-mode components of an input signal and
removes common-mode components. This balanced
amplifier can remove noise mixed as common-mode
components and double the amplitude of a differential
signal as compared with the amplitude of a single-ended
signal. Owing to such advantages, the balanced
amplifier is widely used in analog-digital mixed
integrated circuits and circuits that operate at low

voltages. A circuit for removing common-mode
components has been proposed (Jpn. Pat. Appln. KOKAI
Publication No. 2000-148262) which is configured by
a combination of a differential pair and a common-mode
5 feedback (to be referred to as CMFB hereinafter)
circuit and removes common-mode components from
an input voltage.

In such a conventional circuit, since the common-
mode component removing property of the differential
10 pair is used, the number of cascaded transistors which
are stacked is limited, and the maximum value of an
output signal amplitude is too small when this circuit
operates at a low voltage.

For example, in many semiconductor integrated
15 circuits, analog circuits are formed on the same chip
on which digital circuits are fabricated. In order to
increase the integration degree of circuits, it is
advantageous that digital and analog circuits operate
at the same voltage. With advances in microprocessing,
20 however, the power supply voltage is further decreased.
For example, the operating voltage for a digital
circuit in a 0.11-μm process integrated circuit that
is expected to be commercialized in the near future is
about 1.5V. With a reduction in the size of a process
25 integrated circuit, the operating voltage is expected
to further decrease. When the power supply voltage
further decreases in this manner, the differential

pair cannot exhibit sufficient performance, i.e., a
sufficient output amplitude cannot be obtained, when it
is operated at the same voltage as that for the digital
circuit. Therefore, it may become difficult to obtain

5   a sufficient noise removing effect even if a noise
removing circuit is formed by using a balanced
amplifier.

It is an object of the present invention to
provide a balanced amplifier in which the upper limit

10   of output signal amplitudes is high even at a low
voltage and a filter which uses the balanced amplifier
and can exhibit sufficient performance even at a low
voltage.

BRIEF SUMMARY OF THE INVENTION

15   According to an aspect of the invention, there is
provided a balanced amplifier comprising: a pair of
voltage-to-current converters each including a first
input terminal, a second input terminal, a first output
terminal and a second output terminal, each of the

20   voltage-to-current converters converting differential
input voltages applied to the first input terminals of
the converters into output currents output from both
of the first output terminal and the second output
terminal of each of the converters, wherein the second

25   input terminals and the second output terminals of the
converters are connected in common to cancel common-
mode components and extract differential components.

According to another aspect of the invention, there is provided a balanced amplifier comprising a first voltage-to-current converter and a second voltage-to-current converter, each of the first

5 voltage-to-current converter and the second voltage-to-current converter including a first input terminal, a second input terminal, a first current source which outputs a first current, a second current source which outputs a second current, a first output terminal

10 outputting a third current and a second output terminal outputting a fourth current, wherein the third current is obtained by subtracting a sum current from the first current, the sum current corresponding to sum of currents corresponding to voltages applied to the

15 first input terminal and the second input terminal respectively, and the fourth current being obtained by subtracting the sum current from the second current, and wherein the second input terminal and second output terminal of the first voltage-to-current converter and

20 the second input terminal and second output terminal of the second voltage-to-current converter is connected in common, a differential input signal is input to the first input terminals of the first voltage-to-current converter and the second voltage-current converter,

25 and a differential output signal is output from the first output terminal of the first voltage-to-current converter and the second voltage-current converter.

According to another aspect of the invention, there is provided a balanced amplifier comprising a first voltage-to-current converter and a second voltage-to-current converter, each of the first voltage-to-current converter and the second voltage-to-current converter including a first input terminal, a second input terminal, a first output terminal and a second output terminal, and each supplying a current corresponding to sum of currents corresponding to voltages applied to the first input terminal and the second input terminal respectively to the first output terminal and the second output terminal so that a polarity of an output signal from the first output terminal is reversed with respect to a polarity of an input signal to the first input terminal, and a polarity of an output signal from the second output terminal is reversed with respect to a polarity of an input signal to the second input terminal, wherein the second input terminals and second output terminals of the converters is connected in common, a differential input signal is input to the first input terminals of the converters, and a differential output signal is output from the first output terminals of the converters.

According to another aspect of the invention, there is provided a voltage-to-current converter comprising a first input terminal, a second input

terminal, a first output terminal, a second output
terminal, an adder which adds voltage signals supplied
to the first input terminal and the second input
terminal respectively, a first inverting amplifier

5   which reverses and amplifies an output of the adder; a
second inverting amplifier which reverses and amplifies
the output of the adder, a third inverting amplifier
which reverses and amplifies an output of the first
inverting amplifier and outputs a first reversed and

10   amplified signal to the first output terminal as
a first current signal; a fourth inverting amplifier
which reverses and amplifies an output of the second
inverting amplifier and outputs a second reversed and
amplified signal to the second output terminal as a

15   second current signal; a first capacitor connected
between an input terminal and an output terminal of
the third inverting amplifier, and a second capacitor
connected between an input terminal and an output
terminal of the fourth inverting amplifier.

20   BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING
FIG. 1 is a block diagram of a balanced amplifier
according to the first embodiment of the present
invention;
FIG. 2 is a block diagram of a balanced amplifier

25   according to the second embodiment of the present
invention;
FIG. 3 is a block diagram of a balanced amplifier

according to the third embodiment of the present
invention;

FIG. 4 is a block diagram of a balanced amplifier
according to the fourth embodiment of the present
invention;

FIG. 5 is a block diagram of a balanced amplifier
according to the fifth embodiment of the present
invention;

FIG. 6 is a block diagram of a balanced amplifier
according to the sixth embodiment of the present
invention;

FIG. 7 is a circuit diagram showing an example
of a single input/single output voltage-to-current
converter in FIG. 5;

FIG. 8 is a circuit diagram showing an example
of the practical arrangement of a voltage-to-current
converter when a common source first-stage amplifier is
used for each of the voltage-to-current converters Gm1
to Gm3 in FIGS. 1 to 6;

FIG. 9 is a circuit diagram showing an example
of the practical arrangement of a voltage-to-current
converter when a common source first-stage amplifier is
used for each of the voltage-to-current converters Gm1
to Gm3 in FIGS. 1 to 6;

FIG. 10 is a circuit diagram showing an example
of the practical arrangement of a voltage-to-current
converter when a common source two-stage amplifier is

used for each of the voltage-to-current converters Gm1 to Gm3 in FIGS. 1 to 6;

FIG. 11 is a block diagram of a fifth-order leapfrog filter to which the balanced amplifier according to the seventh embodiment of the present invention is applied; and

FIG. 12 is a block diagram of a voltage-to-current converter according to the eighth embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

A balanced amplifier and a filter using it according to the present invention will be described below with reference to the views of the accompanying drawing.

(First Embodiment)

According to the first embodiment of the present invention shown in FIG. 1, a balanced amplifier comprises voltage-to-current converters Gm1 and Gm2 each having four terminals, namely negative phase input terminals in1 and in2 and positive phase output terminals out1 and out2. The positive phase output terminal out2 and negative phase input terminal in2 of the voltage-to-current converter Gm1, and the positive phase output terminal out2 and negative phase input terminal in2 of the voltage-to-current converter Gm2 are commonly connected. Differential input signals are input from the negative phase input terminal in1 of the

voltage-to-current converter Gm1 and the negative phase input terminal in1 of the voltage-to-current converter Gm2. Differential output signals are output from both the positive phase output terminal out1 of the voltage-to-current converter Gm1 and the positive phase output terminal out1 of the voltage-to-current converter Gm2.

The operations of the voltage-to-current converters Gm1 and Gm2 will be described. Each of the voltage-to-current converters Gm1 and Gm2 converts input voltages to the negative phase input terminals in1 and in2 into currents and outputs them to both the positive phase output terminals out1 and out2. The output from the positive phase output terminal out1 depends on both the negative phase input terminals in1 and in2. Likewise, the output from the positive phase output terminal out2 depends on both the negative phase input terminals in1 and in2.

The operation of the balanced amplifier according to this embodiment will be described next. For the sake of simple explanation, assume that the currents output from the positive phase output terminals out1 and out2 of the voltage-to-current converters Gm1 and Gm2 are always equal. In practice, however, the output current from the positive phase output terminal out1 may differ from the output current from the positive phase output terminal out2.

Letting V1 be the input voltage to the

voltage-to-current converter Gm1, V2 be the input
voltage to the voltage-to-current converter Gm2, 2Vin
be the differential component of the input voltage,
and Vcm be a common-mode component, V1 = Vin + Vcm and
V2 = -Vin + Vcm. Letting Gm be the transconductances
of the voltage-to-current converters Gm1 and Gm2, I1 be
the outputs from the positive phase output terminals
out1 and out2 of the voltage-to-current converter Gm1,
I2 be the outputs from the positive phase output
terminals out1 and out2 of the voltage-to-current
converter Gm2, and Va be the potential on a line
connecting the four terminals in2 and out2 of the
voltage-to-current converters Gm1 and Gm2, output
currents are obtained by converting input voltages and
given by I1 = -Gm(V1 + Va) and I2 = -Gm(V2 + Va).
Since the input impedances of the voltage-to-current
converters Gm1 and Gm2 are very high, the fed-back
currents cannot flow into either of the negative phase
input terminals in2 of the voltage-to-current
converters Gm1 and Gm2. Therefore, n + I2 = 0.

When Va, I1, and I2 are calculated from
I1 = -Gm(V1 + Va) and I2 = -Gm(V2 + Va), Va = -Vcm,
n = -Gm·Vin, I2 = Gm·Vin. As is obvious, therefore,
a feedback is applied to the negative phase input
terminal in2 to cancel out a common-mode component, and
the common-mode component is removed from the output
current.

FIG. 8 shows the first practical arrangement
example of the voltage-to-current converters Gm1 and
Gm2 used in this embodiment. The circuit shown in
FIG. 8 is comprised of a power supply line having a

5   potential Vdd, a power supply line having a potential
Vss, negative phase input terminals in1 and in2,
positive phase output terminals out1 and out2, current
sources J1 and J2, and n-channel transistors M1 to M4
which receive signals from the input terminals.

10   The sources of the n-channel transistors M1 to M4
are connected to the power supply line having the
potential Vss, and one terminal of each of the current
sources J1 and J2 is connected to the power supply line
having the potential Vdd. The other terminal of the

15   current source J1 and the drains of the transistors M1
and M2 are commonly connected. The positive phase
output terminal out1 is connected to this connecting
line. The other terminal of the current source J2 and
the drains of the transistors M3 and M4 are commonly

20   connected, and the positive phase output terminal out2
is connected to this connecting line. The gates of
the transistors M2 and M4 are connected to each other,
and the negative phase input terminal in2 is connected
to this connecting line. With this arrangement,

25   a two-input/two-output voltage-to-current converter is
formed.

The operation of the voltage-to-current converter

shown in FIG. 8 will be described. Operation
associated with an output current from the positive
phase output terminal out1 will be described first.

A current corresponding to an input voltage to
the negative phase input terminal in1 flows in the
drain-to-source path of the transistor M1. Likewise,
a current corresponding to an input voltage to the
negative phase input terminal in2 flows in the
drain-to-source path of the transistor M2. With this
operation, an output current from the positive phase
output terminal out1 is equal to the current obtained
by subtracting the sum of currents corresponding to the
input voltages to the negative phase input terminals
in1 and in2 from the current supplied from the current
source J1. This also applies to the positive phase
output terminal out2. That is, an output current from
the positive phase output terminal out2 is equal to the
current obtained by subtracting the sum of currents
corresponding to the input voltages to the negative
phase input terminals in1 and in2 from the current
supplied from the current source J2.

In the current-to-voltage converter shown in
FIG. 8, letting Vsat be the saturation voltage of each
transistor, and Vt is a threshold voltage, a maximum
value Vmax of an output signal amplitude is the value
obtained by subtracting the terminal-to-terminal
voltage of the current source J1, the drain-to-source

voltage of the transistor M1, and Vss from the
operating voltage Vdd. The current source J1 generally
has a transistor to the gate of which a predetermined
voltage is applied. In addition, the potential

5   difference between the two terminals needs to be at
least Vsat in order to make this arrangement operate
as a current source. Therefore, Vmax = Vdd - Vsat -
Vsa - Vss = Vdd - 2sat - Vss.

If, for example, the power supply voltage Vdd is

10   0.2V; the threshold voltage Vt, 0.5V; power supply
voltage Vdd, 1.0V; and Vss, 0V (ground), then Vmax =
0.6V. That is, the maximum value of the output signal
amplitude increases as compared with the conventional
balanced amplifier comprising a combination of a

15   differential pair and CMFB circuit. It is expected
that this amplifier can exhibit sufficient performance
even at a voltage lower than that for the conventional
balanced amplifier.

FIG. 9 shows the second practical arrangement

20   example of the voltage-to-current converters Gm1 and
Gm2 used in this embodiment. This circuit comprises
a power line 91 having a potential Vdd, a power line 92
having a potential Vss, negative phase input terminals
in1 and in2, positive phase output terminals out1 and

25   out2, n-channel transistors M1 to M8, and p-channel
transistors M9 to M12.

The sources of the transistors M1 to M8 are

connected to the power line 92. The sources of the transistors M9 to M12 are connected to the power line 91. The drains of the transistors M5, M6, and M11 are commonly connected. The positive phase output terminal out1 is connected to this connecting line. The drains of the transistors M7, M8, and M12 are commonly connected. The positive phase output terminal out2 is connected to this connecting line. The gates of the transistors M5 and M7 are connected to each other. The negative phase input terminal in1 is connected to this connecting line. The gates of the transistors M6 and M8 are connected to each other. The negative phase input terminal in2 is connected to this connecting line. The gates of the transistors M1 and M3 are connected to each other. A positive phase input terminal in3 is connected to this connecting line. The gates of the transistors M2 and M4 are connected to each other. A positive phase output terminal in4 is connected to this connecting line. The gate of the transistor M11, the gate and drain of the transistor M10, and the drains of the transistors M3 and M4 are commonly connected. Likewise, the gate of the transistor M12, the gate and drain of the transistor M9, and the drains of the transistors M1 and M2 are commonly connected. With this arrangement, a negative phase two-input/positive phase two-input/positive phase two-output voltage-to-current converter is formed.

The operation of the voltage-to-current converter in FIG. 9 will be described.

A current equal to the sum of currents corresponding to input voltages to the positive phase input terminals in3 and in4 flows in the source-to-drain path of the transistor M10. The transistors M10 and Mn comprises a current mirror, and hence a current flowing in the source-to-drain path of the transistor M11 is controlled by the positive phase input terminals in3 and in4. Likewise, a current flowing between the source and drain of the transistor M12 is controlled by the positive phase input terminals in3 and in4. That is, the transistors M11 and M12 serve as variable current sources controlled by the positive phase input terminals in3 and in4.

In the voltage-to-current converter in FIG. 9, therefore, since the constant current sources J1 and J2 in FIG. 8 are replaced with the transistors M11 and M12 serving as variable current sources, each of output currents from the positive phase output terminals out1 and out2 is equal to the current obtained by subtracting the sum of currents corresponding to input voltages to the negative phase input terminals in1 and in2 from a current equal to the sum of currents corresponding to input voltages to the positive phase input terminals in3 and in4.

In the voltage-to-current converter used in the

circuit shown in FIG. 1, the positive phase input
terminals in3 and in4 shown in FIG. 9 are connected to
predetermined potential points and shielded from
the outside of the voltage-to-current converter so as

5   not to receive any input from the outside of this
converter. The present invention is not limited to
this arrangement, and an arrangement in which the
positive phase input terminals in3 and in4 can receive
inputs from the outside may be used. In this case, as

10   the voltage-to-current converter in FIG. 1, a single-
step-amplification voltage-to-current converter with
a negative phase two-input/positive phase two-input/
positive phase two-output is used.

The voltage-to-current converter in FIG. 9 has the

15   arrangement of a common source amplifier in which the
number of transistors connected in series between the
power lines 91 and 92 is limited to two or less, and
hence the maximum value of an output signal amplifier
is larger than that in the prior art.

20   In the voltage-to-current converter in FIG. 9,
letting Vsat be the saturation voltage of each
transistor, and Vt be a threshold voltage, a maximum
value Vmax of an output signal amplitude is equal to
the value obtained by subtracting the drain-to-source

25   voltage of the transistors M8 and M12 and Vss from
an operating voltage Vdd. Therefore, Vmax = Vdd -
Vsat - Vsat - Vss = Vdd - 2sat - Vss.

If, for example, the saturation voltage Vsat of
each transistor is 0.2V; the threshold voltage Vt,
0.5V; the power supply voltage Vdd, 1.0V; and Vss, 0V
(ground), then Vmax = 0.6V. That is, the maximum value

5   of the output signal amplitude increases as compared
with the conventional balanced amplifier comprising
a combination of a differential pair and CMFB circuit.
It is expected that this amplifier can exhibit
sufficient performance even at a voltage lower than

10   that for the conventional balanced amplifier.

FIG. 10 shows the third practical arrangement
example of the voltage-to-current converters Gm1 and
Gm2 used in this embodiment. This voltage-to-current
converter comprises a power supply line 101 having

15   a potential Vdd, a power supply line 102 having
a potential Vss, negative phase input terminals in1
and in2, n-channel transistors M1 to M6, p-channel
transistors M7 to M12, capacitors C1 and C2, and
positive phase output terminals out1 and out2.

20   The sources of the transistors M1 to M6 are
connected to the power supply line 102, and the sources
of the transistors M7 to M12 are connected to the
power supply line 101. A common bias voltage is
applied to the gates of the transistors M7 to M12.

25   The transistors M7 to M12 function as current sources.

The overall circuit shown in FIG. 10 serves as
a voltage-to-current converter having a negative phase

two input and positive phase two-output. This circuit
can be broken down, in terms of function, into a
two-input/one-output voltage-to-current converter 103,
one-input/one-output current-to-voltage converter 104,

5   one-input/one-output amplifier 105, and
one-input/two-output amplifier 106.

Two input signals input to the negative phase
input terminals in1 and in2 are input to the
voltage-to-current converter 103 and become two final

10   output signals upon sequentially passing through the
one-input/one-output current-to-voltage converter 104,
one-input/one-output amplifier 105, and
one-input/two-output amplifier 106. These signals are
then output from the positive phase output terminals

15   out1 and out2.

The two-input/one-output voltage-to-current
converter 103 comprises transistors M1, M2, M7, and M8.
The drains of these four transistors are mutually
connected. Signals are output from the line which

20   connects the drains to a circuit on the output stage.

The one-input/one-output current-to-voltage
converter 104 comprises the transistors M3 and M9.
The gate and drain of the transistor M3 and the drain
of the transistor M9 are connected to each other.

25   Signals are received on this connecting line from the
circuit on the input side and output to the circuit on
the output stage.

The one-input/one-output amplifier 105 is comprised of transistors M4 and M10. A signal is input from the circuit on the input side to the gate of the transistor M4. The drains of the transistors M4 and

5   M10 are connected to each other. Signals are output from this connecting line to the circuit on the output stage.

The one-input/two-output amplifier 106 is comprised of the transistors M5, M6, M11, and M12 and

10   the capacitors C1 and C2. The gates of the transistors M5 and M6 are connected to each other. Signals from the circuit on the input side are input on this connecting line. The drains of the transistors M5 and M11 are connected to each other. The positive phase

15   output terminal out1 is connected to this connecting line. Likewise, the drains of the transistors M6 and M12 are connected to each other. The positive phase output terminal out2 is connected to this connecting line. The gates and drains of the transistors M5 and

20   M6 are connected through the capacitors C1 and C2 for phase compensation.

The voltage-to-current converters Gm1 and Gm2 used in the circuit in FIG. 1 are formed by using the transistors M7 to M12 serving as constant current

25   sources. A gate voltage Vbias is applied from a constant power supply line to the transistors M7 to M12 in FIG. 10. However, the voltage-to-current converters

Gm1 and Gm2 are not limited to this circuit arrangement and may have a bias circuit and positive phase input terminals in3 and in4 in addition to the components of the circuit in FIG. 10. This circuit may be designed to control a bias circuit for applying Vbias upon reception of inputs from the outside of the positive phase input terminals in3 and in4. In this case, as the voltage-to-current converter in FIG. 1, a two-step-amplification voltage-to-current converter with a negative phase two-input/positive phase two-input/positive phase two-output is used.

Since the voltage-to-current converter in FIG. 10 has a common source amplifier arrangement in which the number of cascaded transistors between the power supply lines 101 and 102 is limited to two or less, the maximum value of an output signal amplitude is larger than that in the prior art. In addition, since the voltage-to-current converter has two amplifiers, the transconductance of the voltage-to-current converter can be increased.

In the voltage-to-current converter in FIG. 10, letting Vsat be the saturation voltage of each transistor and Vt be a threshold voltage, a maximum value Vmax of an output signal amplitude is equal to the value obtained by subtracting the drain-to-source voltage of the transistors M8 and M12 and Vss from an operating voltage Vdd, i.e.,

$$Vmax = Vdd - Vsat - Vsat - Vss = Vdd - 2sat - Vss.$$

If, for example, the saturation voltage Vsat of

each transistor is 0.2V; the threshold voltage Vt,

0.5V; power supply voltage Vdd, 1.0V; and Vss, 0V

5   (ground), then Vmax = 0.6V. That is, the maximum value

of the output signal amplitude increases as compared

with the conventional balanced amplifier comprising

a combination of a differential pair and CMFB circuit.

It is expected that this amplifier can exhibit

10   sufficient performance even at a voltage lower than

that for the conventional balanced amplifier.

(Second Embodiment)

FIG. 2 is a block diagram showing a balanced

amplifier according to the second embodiment of

15   the present invention. This balanced amplifier is

a voltage-input/voltage-output balanced amplifier

comprised of voltage-to-current converters Gm1 and Gm2

each having four terminals, namely negative phase

input terminals in1 and in2 and positive phase output

20   terminals out1 and out2, an impedance element 21a

connected in parallel between the negative phase input

terminal in1 and positive phase output terminal out1 of

the voltage-to-current converter Gm1, and an impedance

element 21b connected in parallel between the negative

25   phase input terminal in1 and positive phase output

terminal out1 of the voltage-to-current converter Gm2.

The four terminals, i.e., negative phase input

terminals in2 and positive phase output terminals out2
of the voltage-to-current converters Gm1 and Gm2 are
connected to each other.

The operation of the balanced amplifier according
to this embodiment will be described next. For the
sake of simple explanation, assume that the currents
output from the positive phase output terminals out1
and out2 of the voltage-to-current converters Gm1 and
Gm2 are always equal.

Let V1 be the input voltage to the voltage-to-
current converter Gm1, V2 be the input voltage to
the voltage-to-current converter Gm2, 2Vin be the
differential component of the input voltage, Vcm be the
common-mode component, Gm be the transconductance of
each of the voltage-to-current converters Gm1 and Gm2,
Z1 be the impedance of each of the impedance elements
21a and 21b, V3 be the output voltage from the positive
phase output terminal out1 of the voltage-to-current
converter Gm1, V4 be the output voltage from the
positive phase output terminal out1 of the voltage-to-
current converter Gm2, I1 be the output current from
each of the positive phase output terminals out1 and
out2 of the voltage-to-current converter Gm1, I2 be the
output current from the positive phase output terminals
out1 and out2 of the voltage-to-current converter Gm2,
and Va be the potential of a line connecting the
terminals out2 and in2 of the voltage-to-current

converters Gm1 and Gm2.

The voltage-to-current converters Gm1 and Gm2 convert input voltages into currents and output them. The relationships between the input voltages and the output currents are represented by $I1 = -Gm(V1 + Va)$ and $I2 = -Gm(V2 + Va)$. Since the balanced amplifier of this embodiment is generally used to output an output signal to a circuit having a high input impedance, such as a buffer circuit, all output currents are fed back as long as the amplifier is used in a general manner. Therefore, $V3 = V1 + I1 \cdot Z1$ and $V4 = V2 + I2 \cdot Z1$. Since the currents output to the positive phase output terminals out2 of the voltage-to-current converters Gm1 and Gm2 cannot flow into either negative phase input terminal in2, $I1 + I2 = 0$. Since $V1 = Vin + Vcm$ and $V2 = -Vin + Vcm$, Va, V3, and V4 are calculated as $Va = -Vcm$, $V3 = Vcm - Vin - Gm \cdot Z1 \cdot Vin$, and $V4 = Vcm - Vin + Gm \cdot Z1 \cdot Vin$.

In general, since a high differential voltage gain is set ($Gm \cdot Z1 \gg 1$ in this embodiment), V3 to $Vcm - Gm \cdot Z1 \cdot Vin$ and V4 to $Vcm + Gm \cdot Z1 \cdot Vin$. That is, the input differential voltage is multiplied by $Gm \cdot Z1$, and the input common-mode voltage appears at the output without any change. Since a common-mode rejection ratio (to be referred to as a CMRR) is defined by (differential voltage gain)/(common-mode voltage gain), the CMRR of the circuit of this embodiment is

represented by $Gm \cdot Z1$.   Since $Gm \cdot Z1 >> 1$, a high CMRR can be obtained.

In this embodiment, as the voltage-to-current converters Gm1 and Gm2, for example, the circuits shown
5   in FIGS. 8 to 10 may be used.   The negative phase input terminals in the voltage-to-current converter in FIG. 9 are handled in the above manner.   This circuit is used as a negative phase two-input/positive phase two-output voltage-to-current converter.   However, the present
10   invention is not limited to this.   For example, as the voltage-to-current converters Gm1 and Gm2 in this embodiment, the above circuit in FIG. 9 formed as a negative phase two-input/positive phase two-input/ positive phase two-output voltage-to-current converter
15   may be used.

As described above, by using these voltage-to- current converters, a high output amplitude limit can be obtained even in low-voltage operation as compared with a conventional balanced amplifier comprising
20   a combination of a differential pair and CMFB circuit. In addition, the circuit in FIG. 10 can increase the transconductance Gm as compared with the circuits shown in FIGS. 8 and 9, the CMRR can be increased as compared with a case wherein the circuits shown in FIGS. 8 and 9
25   are used.

The advantages of this embodiment are that a considerably high CMRR corresponding to the gain

of an amplifier can be obtained, and a high output
signal amplitude limit can be obtained in low-voltage
operation as compared with the prior art.

(Third Embodiment)

5   FIG. 3 is a block diagram showing a balanced
amplifier according to the third embodiment of
the present invention. This balanced amplifier is
a voltage-input/voltage-output balanced amplifier
comprised of voltage-to-current converters Gm1 and

10   Gm2 each having four terminals, namely negative phase
input terminals in1 and in2 and positive phase output
terminals out1 and out2, an impedance element 31a
connected in parallel between the negative phase input
terminal in1 and positive phase output terminal out1 of

15   the voltage-to-current converter Gm1, an impedance
element 31b connected in parallel between the negative
phase input terminal in1 and positive phase output
terminal out1 of the voltage-to-current converter Gm2,
an impedance element 32a having one terminal connected

20   to the negative phase input terminal in1 of the
voltage-to-current converter Gm1, and an impedance
element 32b having one terminal connected to the
negative phase input terminal in1 of the voltage-to-
current converter Gm2. The negative phase input

25   terminals in2 and positive phase output terminals out2
of the voltage-to-current converters Gm1 and Gm2 are
connected to each other.

The operation of the balanced amplifier according to this embodiment will be described next. For the sake of simple explanation, assume that the currents output from the positive phase output terminals out1 and out2 of the voltage-to-current converters Gm1 and Gm2 are always equal. In practice, however, these output currents may differ from each other.

Let V1 be the input voltage to the impedance element 32a side of the balanced amplifier according to this embodiment, V2 be the input voltage to the impedance element 32b side, 2Vin be the differential component of the input voltages, Vcm be the common-mode component, Gm be the transconductance of each of the voltage-to-current converters Gm1 and Gm2, Z1 be the impedance of each of the impedance elements 31a and 31b, Z2 be the impedance of each of the impedance elements 32a and 32b, V3 be the output voltage from the positive phase output terminal out1 of the voltage-to-current converter Gm1, V4 be the output voltage from the positive phase output terminal out1 of the voltage-to-current converter Gm2, I1 be the output current from each of the positive phase output terminals out1 and out2 of the voltage-to-current converter Gm1, I2 be the output current from each of the positive phase output terminals out1 and out2 of the voltage-to-current converter Gm2, Va be the potential of a line connecting the negative phase input terminal in1 of the

voltage-to-current converter Gm1 and the impedance elements 31a and 32a, Vb be the potential of a line connecting the negative phase input terminal in1 of the voltage-to-current converter Gm2 and the impedance elements 31b and 32b, and Vc be the potential of a line connecting the four terminals out2 and in2 of the voltage-to-current converters Gm1 and Gm2.

The voltage-to-current converters Gm1 and Gm2 convert input voltages into currents. The relationships between the input voltages and the output currents are represented by I1 = -Gm(Va + Vc) and I2 = -Gm(Vb + Vc). Since the balanced amplifier of this embodiment is generally used to output an output signal to a circuit having a high input impedance, such as a buffer circuit, all output currents are fed back as long as the amplifier is used in a general manner. Therefore, V3 = Va + I1·Z1 and V4 = Vb + I2·Z1. Since the currents output to the positive phase output terminals out2 of the voltage-to-current converters Gm1 and Gm2 cannot flow into either negative phase input terminal in2, I1 + I2 = 0. Since the impedance of the negative phase input terminal in1 is very high, the current fed back from the positive phase output terminal out1 cannot flow into the negative phase input terminal in1. Therefore, Va = V1 + I1·Z2 and Vb = V2 + I2·Z2. In addition, since V1 = Vin + Vcm and V2 = -Vin + Vcm, Va, Vb, Vc, V3, and V4 are given by:

$$Va = \frac{Vin + Vcm + Gm \bullet Z2 \bullet Vcm}{Gm \bullet Z2 + 1}$$

$$Vb = \frac{-Vin + Vcm + Gm \bullet Z2 \bullet Vcm}{Gm \bullet Z2 + 1}$$

$$Vc = -Vcm$$

$$V3 = \frac{Vin + Vcm - Gm \bullet Z1 \bullet Vin + Gm \bullet Z2 \bullet Vcm}{Gm \bullet Z2 + 1}$$

$$V4 = \frac{-Vin + Vcm + Gm \bullet Z1 \bullet Vin + Gm \bullet Z2 \bullet Vcm}{Gm \bullet Z2 + 1}$$

In this case, if Gm·Z1 >> 1 and Gm·Z2 >> 1, minute terms can be neglected, and the above values can be expressed as:

$$Va \cong Vcm$$

$$Vb \cong Vcm$$

$$Vc \cong -Vcm$$

$$V3 \cong Vcm - \frac{Z1}{Z2} Vin$$

$$V4 \cong Vcm + \frac{Z1}{Z2} Vin$$

Obviously, therefore, the input differential voltage is multiplied by Z1/Z2, but the input common-mode voltage appears at the output without any change. Since the CMRR of the circuit according to this embodiment becomes Z1/Z2, and the circuit is generally designed to set the differential voltage gain to (Z1/Z2) >> 1, a high CMRR can be obtained. In addition, since the differential voltage gain is determined by the magnitudes of Z1 and Z2, even if

the transconductance Gm varies due to changes in temperature or time-varying factors, the differential voltage gain can be kept constant.

In this embodiment, as the voltage-to-current converters Gm1 and Gm2, for example, the circuits shown in FIGS. 8 to 10 may be used. The negative phase input terminals in the voltage-to-current converter in FIG. 9 are handled in the above manner. This circuit is used as a negative phase two-input/positive phase two-output voltage-to-current converter. However, the present invention is not limited to this. For example, as the voltage-to-current converters Gm1 and Gm2 in this embodiment, the above circuit in FIG. 9 or 10 formed as a negative phase two-input/positive phase two-input/ positive phase two-output voltage-to-current converter may be used. By using these circuits as the voltage-to-current converters Gm1 and Gm2, the maximum value of an output signal amplitude increases as compared with the conventional balanced amplifier obtained by combining the differential pair and the CMFB circuit.

The advantages of this embodiment are that a CMRR equivalent in magnitude to the gain of an amplifier can be obtained, a CMRR can be determined by a relatively stable value, i.e., the ratio between the impedance values of impedance elements and is not dependent on a value that tends to vary, e.g., a transconductance value, and a high output signal amplitude can be

obtained even at a low operating voltage if the
circuits shown in FIGS. 8 to 10 are used as the
voltage-to-current converters Gm1 and Gm2.

(Fourth Embodiment)

5   FIG. 4 is a block diagram of a balanced amplifier
according to the fourth embodiment of the present
invention. This balanced amplifier is a voltage-input/
voltage-output balanced amplifier comprising voltage-
to-current converters Gm1, Gm2, and Gm3, each having

10   negative phase input terminals in1 and in2, positive
phase input terminals in3 and in4, and positive phase
output terminals out1 and out2, an impedance element
41a connected in parallel between the negative phase
input terminal in1 and positive phase output terminal

15   out1 of the voltage-to-current converter Gm1, an
impedance element 41b connected in parallel between
the negative phase input terminal in1 and positive
phase output terminal out1 of the voltage-to-current
converter Gm2, an impedance element 42a having one

20   terminal connected between the negative phase input
terminal in1 of the voltage-to-current converter Gm1
and the impedance element 41a, and an impedance element
42b having one terminal connected between the negative
phase input terminal in1 of the voltage-to-current

25   converter Gm2 and the impedance element 41b. The
positive phase input terminals in3 and in4 of the
voltage-to-current converters Gm1 and Gm2 are connected

to a common potential. The four terminals, i.e., the
negative phase input terminals in2 and positive phase
output terminals out2, of the voltage-to-current
converters Gm1 and Gm2 are connected to each other.

5   The negative phase input terminal in1 and positive
phase output terminal out1 of the voltage-to-current
converter Gm3 are connected to the negative phase input
terminal in1 of the voltage-to-current converter Gm1.
The negative phase input terminal in2 and positive

10 phase output terminal out2 of the voltage-to-current
converter Gm3 are connected to the negative phase input
terminal in1 of the voltage-to-current converter Gm2.
The positive phase input terminals in3 and in4 of
the voltage-to-current converter Gm3 are connected to

15 a common potential.

The operation of the balanced amplifier according
to this embodiment will be described next. For the
sake of simple explanation, assume that the currents
output from the positive phase output terminals out1

20 and out2 of the voltage-to-current converters Gm1
and Gm2 are always equal. This also applies to the
voltage-to-current converters Gm2 and Gm3. However,
output currents from the voltage-to-current converters
Gm1 and Gm2 need not be equal.

25 Let V1 be the input voltage to the impedance
element 42a side of the balanced amplifier according
to this embodiment, V2 be the input voltage to the

impedance element 42a side, 2Vin be a differential
component of the input voltage, Vcm be the common-mode
component, Gma be the transconductance of each of the
voltage-to-current converters Gm1 and Gm2, Gmb be the
transconductance of the voltage-to-current converter
Gm3, Z1 be the impedance of each of the impedance
elements 41a and 41b, Z2 be the impedance of each of
the impedance elements 42a and 42b, V3 be the output
voltage from the positive phase output terminal out1 of
the voltage-to-current converter Gm1, V4 be the output
voltage from the positive phase output terminal out1 of
the voltage-to-current converter Gm2, I1 be the output
current from each of the positive phase output
terminals out1 and out2 of the voltage-to-current
converter Gm1, I2 be the output current from each of
the positive phase output terminals out1 and out2 of
the voltage-to-current converter Gm2, I3 be the output
current from each of the positive phase output
terminals out1 and out2 of the voltage-to-current
converter Gm3, Va be the potential of the negative
phase input terminal in1 of the voltage-to-current
converter Gm1, Vb be the potential of the negative
phase input terminal in1 of the voltage-to-current
converter Gm2, Vc be the potential of each of the
negative phase input terminals in2 of the voltage-to-
current converters Gm1 and Gm2, Vref1 be the reference
voltage input to each of the positive phase input

terminals in3 and in4 of the voltage-to-current converters Gm1 and Gm2, and Vref2 be the reference voltage input to each of the positive phase input terminals in3 and in4 of the voltage-to-current

5   converter Gm3.

The voltage-to-current converters Gm1, Gm2, and Gm3 convert input voltages into currents and output them. The relationships between the input voltages and the output currents are represented by

10 $I1 = Gma(2Vref1 - Va - Vc)$, $I2 = Gma(2Vref1 - Vb - Vc)$, and $I3 = Gmb(2Vref2 - Va - Vb)$. Since the balanced amplifier of this embodiment is generally used to output an output signal to a circuit having a high input impedance, such as a buffer circuit, all output

15 currents are fed back as long as the amplifier is used in a general manner. Therefore, $V3 = Va + I1 \cdot Z1$ and $V4 = Vb + I2 \cdot Z1$. Since the currents output to the positive phase output terminals out2 of the voltage-to-current converters Gm1 and Gm2 cannot flow into

20 either negative phase input terminal in2, $I1 + I2 = 0$. Since the impedances of the negative phase input terminals in1 and in2 of the voltage-to-current converter Gm3 are very high, no current can flow into them. Therefore, $Va = V1 + (I1 + I3)Z2$ and $Vb = V2 +$

25 $(I2 + I3)Z2$. Differential input signals to the balanced amplifier according to this embodiment are represented by $V1 = Vin + Vcm$ and $V2 = Vin + Vcm$.

According to the above description, Va, Vb, Vc, V3, and V4 are given by:

$$Va = \frac{Vin + 2Gmb \bullet Z2 \bullet Vin}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)} + \frac{Vcm + Vcm \bullet Gma \bullet Z2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$+ \frac{2Gma \bullet Gmb \bullet Z2^2 \bullet Vref2 + 2Gmb \bullet Z2 \bullet Vref2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$Vb = \frac{-Vin - 2Gmb \bullet Z2 \bullet Vin}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)} + \frac{Vcm + Vcm \bullet Gma \bullet Z2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$+ \frac{2Gma \bullet Gmb \bullet Z2^2 \bullet Vref2 + 2Gmb \bullet Z2 \bullet Vref2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$Vc = \frac{2Vref1 + 4Gmb \bullet Z2 \bullet Vref1}{2Gmb \bullet Z2 + 1} - \frac{Vin}{2Gmb \bullet Z2 + 1} - \frac{2Gmb \bullet Z2 \bullet Vref2}{2Gmb \bullet Z2 + 1}$$

$$V3 = \frac{Vin + 2Gmb \bullet Z2 \bullet Vin - Gma \bullet Z1 \bullet Vin - 2Gma \bullet Gmb \bullet Z1 \bullet Z2 \bullet Vin}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$+ \frac{Vcm + Z2 \bullet Gma \bullet Vcm}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)} + \frac{2Gma \bullet Gmb \bullet Z2^2 \bullet Vref2 + 2Gmb \bullet Z2 \bullet Vref2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$V4 = \frac{-Vin - 2Gmb \bullet Z2 \bullet Vin + Gma \bullet Z1 \bullet Vin + 2Gma \bullet Gmb \bullet Z1 \bullet Z2 \bullet Vin}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

$$+ \frac{Vcm + Z2 \bullet Gma \bullet Vcm}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)} + \frac{2Gma \bullet Gmb \bullet Z2^2 \bullet Vref2 + 2Gmb \bullet Z2 \bullet Vref2}{(Gma \bullet Z2 + 1)(2Gmb \bullet Z2 + 1)}$$

In this case, if Gma·Z1 >> 1, Gmb·Z2 >> 1, and Gma·Z2 >> 1, and minute terms are neglected, the above values can be expressed as:

$$Va \cong Vref2$$

$$Vb \cong Vref2$$

$$Vc \cong 2Vref1 - Vref2$$

$$V3 = -\frac{Z1}{Z2}Vin + \frac{1}{2Gmb \bullet Z2}Vcm + Vref2 = -\frac{Z1}{Z2}Vin + Vref2$$

$$V4 = -\frac{Z1}{Z2}Vin + \frac{1}{2Gmb \bullet Z2}Vcm + Vref2 = \frac{Z1}{Z2}Vin + Vref2$$

Obviously, a differential gain is multiplied by
Z1/Z2 and determined by impedance elements but is not
influenced by variations in transconductance Gm.
In addition, since a common-mode output voltage is
equal to the reference voltage Vref2 input to the
positive phase input terminals in3 and in4 of the
voltage-to-current converter Gm3, the input voltage
Vref to the positive phase input terminals in3 and in4
of the voltage-to-current converter Gm3 becomes a bias
voltage that controls the common-mode output voltage.
If, for example, Vref2 is 0.7V, the common-mode
component of the output voltage also becomes 0.7V.

In this case, if Vref1 = Vref2 = Vref, then
Va = Vb = Vc = Vref. Since input voltages to all the
voltage-to-current converters become equal to each
other, the paths between the input terminals in1, in2,
in3, and in4 of all the voltage-to-current converters
can be regarded as virtual shorts. This makes it
possible to form each of the voltage-to-current
converters Gm1, Gm2, and Gm3 by using transistors with
narrow linear input ranges as transistors which receive
input signals.

As each of the voltage-to-current converters Gm1,
Gm2, and Gm3, the circuit shown in FIG. 9 can be used.

A circuit obtained by adding a circuit capable of controlling bias voltages to be applied to the transistors M7 to M12 by using input voltages to the positive phase input terminals in3 and in4 to the

5 voltage-to-current converter in FIG. 10 may be used as each of the voltage-to-current converters Gm1 to Gm3 according to this embodiment.

The advantages of this embodiment are that a differential gain can be determined by a relatively

10 stable value, i.e., an impedance value ratio, an output voltage operating point can be determined by the voltage externally applied to each positive phase input terminal, and a high output signal amplitude can be obtained even at a low operating voltage as compared

15 with the prior art.

(Fifth Embodiment)

FIG. 5 is a block diagram of a balanced amplifier according to the fifth embodiment of the present invention. Note that a description of a portion common

20 to the fourth embodiment will be omitted.

The balanced amplifier according to this embodiment uses single input/signal output voltage-to-current converters Gm4 and Gm5 instead of the impedance elements 42a and 42b in the fourth embodiment.

25 The balanced amplifier according to this embodiment is a voltage-input/voltage-output balanced amplifier comprising voltage-to-current converters Gm1, Gm2,

and Gm3, each having negative phase input terminals in1 and in2, positive phase input terminals in3 and in4, and positive phase output terminals out1 and out2, an impedance element 51a connected in parallel between

5 the negative phase input terminal in1 and positive phase output terminal out1 of the voltage-to-current converter Gm1, an impedance element 51b connected in parallel between the negative phase input terminal in1 and positive phase output terminal out1 of the voltage-

10 to-current converter Gm2, and the single input/single output voltage-to-current converters Gm4 and Gm5.

The positive phase input terminals in3 and in4 of the voltage-to-current converters Gm1, Gm2, and Gm3 are connected to a common potential. The output terminal

15 of the single input/single output voltage-to-current converter Gm4 is connected to the negative phase input terminal in1 of the voltage-to-current converter Gm1. The output terminal of the single input/single output voltage-to-current converter Gm5 is connected to the

20 negative phase input terminal in1 of the voltage-to-current converter Gm2. The four terminals, i.e., the negative phase input terminals in2 and positive phase output terminals out2, of each of the voltage-to-current converters Gm1 and Gm2 are commonly connected.

25 The negative phase input terminal in1 and positive phase output terminal out1 of the voltage-to-current converter Gm3 are connected to the negative phase input

terminal in1 of the voltage-to-current converter Gm1.
The negative phase input terminal in2 and positive
phase output terminal out2 of the voltage-to-current
converter Gm3 are connected to the negative phase input
5   terminal in1 of the voltage-to-current converter Gm2.
The positive phase input terminals in3 and in4 of each
of the voltage-to-current converters Gm1, Gm2, and Gm3
are connected to a common potential.

The operation of the balanced amplifier according
10   to this embodiment will be described next. For the
sake of simple explanation, assume that the currents
output from the positive phase output terminals out1
and out2 of the voltage-to-current converters Gm1, Gm2,
and Gm3 are always equal.

15   Let V1 be the input voltage to the input terminal
of the single input/single output voltage-to-current
converter Gm4 of the balanced amplifier according to
this embodiment, V2 be the input voltage to the input
terminal of the single input/single output voltage-
20   to-current converter Gm5, 2Vin be the differential
component of the input voltage, Vcm be the common-mode
component, Gma be the transconductance of each of the
voltage-to-current converters Gm1 and Gm2, Gmb be the
transconductance of the voltage-to-current converter
25   Gm3, Gmc be the transconductance of each of the single
input/single output voltage-to-current converters Gm4
and Gm5, Z1 be the impedance of each of the impedance

elements 51a and 51b, V3 be the output voltage from
the positive phase output terminal out1 of the voltage-
to-current converter Gm1, V4 be the output voltage
from the positive phase output terminal out1 of the
voltage-to-current converter Gm2, I1 be the output
current from each of the positive phase output
terminals out1 and out2 of the voltage-to-current
converter Gm1, I2 be the output current from each of
the positive phase output terminals out1 and out2 of
the voltage-to-current converter Gm2, I3 be the output
current from the positive phase output terminals out1
and out2 of the voltage-to-current converter Gm3, Va be
the potential of the negative phase input terminal in1
of the voltage-to-current converter Gm1, Vb be the
potential of the negative phase input terminal in1
of the voltage-to-current converter Gm2, Vc be the
potential of each of the negative phase input terminals
in2 of the voltage-to-current converters Gm1 and Gm2,
and Vref be the bias voltage input to each of the
positive phase input terminals in3 and in4 of the
voltage-to-current converters Gm1, Gm2, and Gm3.

The voltage-to-current converters Gm1, Gm2,
and Gm3 convert input voltages into currents and
output them. The relationships between the input
voltages and the output currents are represented by
$I1 = Gma(2Vref - Va - Vc)$, $I2 = Gma(2Vref - Vb - Vc)$,
and $I3 = Gmb(2Vref - Va - Vb)$. Since the balanced

amplifier of this embodiment is generally used to output an output signal to a circuit having a high input impedance, such as a buffer circuit, all output currents are fed back as long as the amplifier is used in a general manner. Therefore, V3 = Va + I1·Z1 and V4 = Vb + I2·Z1. Since the currents output to the positive phase output terminals out2 of the voltage-to-current converters Gm1 and Gm2 cannot flow into either negative phase input terminal in2, I1 + I2 = 0. Since the impedances of the negative phase input terminals in1 and in2 of the voltage-to-current converters Gm1, Gm2, and Gm3 are very high, no current can flow into them. Therefore, I1 + I3 + Gmc·V1 = 0 and I2 + I3 + Gmc·V2 = 0. Differential input signals to the balanced amplifier according to this embodiment are represented by V1 = Vin + Vcm and V2 = -Vin + Vcm.

According to the above description, V3 and V4 are given by:

$$V3 = \frac{Gma \bullet Gmc \bullet Vcm}{2Gma \bullet Gmb} + \frac{Gma \bullet Gmb \bullet Vref}{Gma \bullet Gmb}$$

$$+ \frac{Gma \bullet Gmc \bullet Vin - Gma \bullet Gmb \bullet Gmc \bullet Z1 \bullet Vin}{Gma \bullet Gmb}$$

$$V4 = \frac{Gma \bullet Gmc \bullet Vcm}{2Gma \bullet Gmb} + \frac{Gma \bullet Gmb \bullet Vref}{Gma \bullet Gmb}$$

$$- \frac{Gma \bullet Gmc \bullet Vin - Gma \bullet Gmb \bullet Gmc \bullet Z1 \bullet Vin}{Gma \bullet Gmb}$$

In this case, if Gma·Z1 >> 1 and Gmb·Z1 >> 1, minute terms can be neglected, and the above values can be

expressed as:

$$V3 \cong \frac{Gmc}{2Gmb} Vcm - Gmc \bullet Z1 \bullet Vin + Vref$$

$$V4 \cong \frac{Gmc}{2Gmb} Vcm + Gmc \bullet Z1 \bullet Vin + Vref$$

As a consequence, the CMRR is given by 2Gmb·Z1, and hence a high CMRR can be obtained. Obviously, in this embodiment as well, Vref serves as a bias voltage for controlling a common-mode output voltage.

As each of the single input/single output voltage-to-current converters Gm4 and Gm5 in this embodiment, for example, a common source transistor circuit like the one shown in FIG. 7 can be used, and hence can be formed by using a very simple circuit.

As each of the voltage-to-current converters Gm1, Gm2, and Gm3 in this embodiment, the circuit shown in FIG. 9 can be used. A circuit obtained by adding a circuit capable of controlling bias voltages to be applied to the transistors M7 to M12 by using input voltages to the positive phase input terminals in3 and in4 to the voltage-to-current converter in FIG. 10 may be used as each of the voltage-to-current converters Gm1 to Gm3 according to this embodiment.

An advantage of this embodiment is that when a filter is formed by using this balanced amplifier as described later, the frequency characteristics of the filter can be easily controlled by changing the value

of Gmc, e.g., the common-mode component Vcm of each
input voltage. The common-mode component Vcm of an
input voltage may be changed by the following method.
For example, another balanced amplifier according to
5   this embodiment is connected to the input stage of the
balanced amplifier of this embodiment, and the bias
voltage to be applied to the balanced amplifier on the
input stage is changed. With this operation, since the
common-mode output voltage Vcm from the input state
10   also changes, and hence the inphase input voltage Vcm
of the balanced amplifier on the output stage changes.
As a consequence, the value of Gmc of the balanced
amplifier on the output stage changes.
(Sixth Embodiment)
15   FIG. 6 is a block diagram showing a balanced
amplifier according to the sixth embodiment of the
present invention. Note that a description of a
portion common to the fifth embodiment will be omitted.
     The balanced amplifier according to this
20   embodiment has two sets of three single input/single
output voltage-to-current converters, which correspond
to the single input/single output voltage-to-current
converters Gm4 an Gm5 of the balanced amplifier
according to the fifth embodiment, thus having inputs
25   of six systems. The balanced amplifier according to
this embodiment is a voltage-input/voltage-output
balanced amplifier comprising voltage-to-current

converters Gm1, Gm2, and Gm3, each having negative

phase input terminals in1 and in2, positive phase input

terminals in3 and in4, and positive phase output

terminals out1 and out2, an impedance element 61a

5   connected in parallel between the negative phase input

terminal in1 and positive phase output terminal out1 of

the voltage-to-current converter Gm1, an impedance

element 61b connected in parallel between the negative

phase input terminal in1 and positive phase output

10   terminal out1 of the voltage-to-current converter Gm2,

and single input/single output voltage-to-current

converters Gm4 to Gm9.

The positive phase input terminals in3 and in4 of

the voltage-to-current converters Gm1, Gm2, and Gm3 are

15   connected to a common potential. The output terminals

of the single input/single output voltage-to-current

converters Gm4, Gm5, and Gm6 are connected to the

negative phase input terminal in1 of the voltage-to-

current converter Gm1. The output terminals of

20   the single input/single output voltage-to-current

converters Gm7, Gm8, and Gm9 are connected to the

negative phase input terminal in1 of the voltage-to-

current converter Gm2. The four terminals, i.e., the

negative phase input terminals in2 and positive phase

25   output terminals out2, of each of the voltage-to-

current converters Gm1 and Gm2 are commonly connected.

The negative phase input terminal in1 and positive

phase output terminal out1 of the voltage-to-current
converter Gm3 are connected to the negative phase input
terminal in1 of the voltage-to-current converter Gm1.
The negative phase input terminal in2 and positive

5   phase output terminal out2 of the voltage-to-current
converter Gm3 are connected to the negative phase input
terminal in1 of the voltage-to-current converter Gm2.
The positive phase input terminals in3 and in4 of
each of the voltage-to-current converters Gm1, Gm2,

10   and Gm3 are connected to a common potential. The
transconductances of the single input/single output
voltage-to-current converters Gm4 to Gm9 are equal to
each other.

        The operation of the balanced amplifier

15   according to this embodiment will be described next.
A description of an operation common to the balanced
amplifier of the fifth embodiment will be omitted.
In the voltage-to-current converters in this
embodiment, the first differential input signal is

20   input to input voltage terminals V1a and V1b of the
single input/single output voltage-to-current
converters Gm4 and Gm7, the second differential input
signal is input to input voltage terminals V2a and V2b
of the single input/single output voltage-to-current

25   converters Gm5 and Gm8, and the third differential
input signal is input to input voltage terminals
V3a and V3b of the single input/single output

voltage-to-current converters Gm6 and Gm9. That is,
the sum of the three differential input signals can be
obtained. This circuit operates in the same manner as
the circuit according to the fifth embodiment except
5   that the sum of the three differential input signals is
obtained, and outputs a differential output signal
corresponding to the sum of the three differential
input signals.

In this embodiment, three differential input
10 signals are received. However, an arrangement designed
to receive more input signals can be easily realized by
increasing the number of single input/single output
voltage-to-current converters in the same manner as in
this embodiment.

15   For the sake of simple explanation, it is assumed
that all the transconductances of the single
input/single output voltage-to-current converters Gm4
to Gm9 are equal. In practice, however, these values
may differ from each other. If, for example, the
20 transconductances of the single input/single output
voltage-to-current converters Gm4 and Gm7 to which the
first differential input signal is input are set to be
higher than those of the remaining converters, the gain
can be increased only for the differential component
25 of the first differential input signal relative to
the differential-mode components of the remaining
differential input signals.

In this embodiment, the numbers of single input/single output voltage-to-current converters connected to the voltage-to-current converters Gm1 and Gm2 are set to be equal. However, these numbers need not always be equal.

This embodiment may use impedance elements instead of the single input/single output voltage-to-current converters Gm4 to Gm9 as in the fifth embodiment which uses the single input/single output voltage-to-current converters Gm4 and Gm5 instead of the impedance elements 42a and 42b (see FIG. 4) in the fourth embodiment. In this case, like the above transconductances, the impedances of the respective impedance elements need not be equal.

In addition to the advantages of the fifth embodiment, this embodiment has the advantage that a multi-input type balanced amplifier can be provided.

(Seventh Embodiment)

FIG. 11 is a block diagram showing a filter to which a balanced amplifier according to an embodiment of the present invention is applied.

The filter of this embodiment is a fifth-order leapfrog filter and comprises multi-input integrators 11 to 15. These multi-input integrators 11 to 15 use capacitors as the impedance elements 61a and 61b (see FIG. 6) in the sixth embodiment of the present invention. Even if multi-input integrators are

required as in this embodiment, a filter that operates

at a low voltage and has a high output signal amplitude

can be realized by using the balanced amplifier of the

present invention.

5   Since the circuit shown in FIG. 6 is used for each

of the integrators 11 to 15 in this embodiment, a

transconductance Gmc of each single input/single output

voltage-to-current converter in FIG. 6 can be changed

by changing the common-mode voltage of an input signal.

10   In addition, since the time constant, i.e., the

frequency characteristic, of the filter circuit of

this embodiment changes in accordance with the value

of Gmc, the frequency characteristic of the filter can

be changed by changing the common-mode component of

15   an input signal.

As described above, the common-mode component of

an output voltage from the balanced amplifier (FIG. 6)

used for the integrators 11 to 15 is determined by the

input voltage Vref to all the positive phase input

20   terminals in3 and in4 of the voltage-to-current

converters Gm1 to Gm3. The common-mode component of

the output voltage becomes substantially equal to Vref.

As the value of Vref changes, the output common-mode

voltage changes. Since the outputs and inputs of

25   the integrators 11 to 15 are connected to each other,

if Vref increases, the input common-mode voltage

increases, and thus the value of Gmc increases. As a

consequence, the time constant of the filter circuit in
FIG. 11 also changes. The frequency characteristics
such as a cutoff frequency, can be changed by changing
Vref in the overall circuit.

5   This embodiment is based on a low pass filter (to
be referred to as an LPF). However, the filter circuit
using the balanced amplifier of the present invention
is not limited to this, and a high pass filter (to be
referred to as an HPF) and a band pass filter (to be
10   referred to as a BPF) can be formed by changing the
arrangement of the filter circuit.

The filter of this embodiment uses a leapfrog
arrangement. However, the filter circuit using the
balanced amplifier of the present invention is not
15   limited to this. With regard to the characteristics
of the filter as well, circuits having various
characteristics, e.g., Butterworth, Chebychev, and
Bessel filters, can be assembled by changing the
characteristics of the integrators used in this
20   embodiment.

FIG. 12 is a block diagram showing a
voltage-to-current converter according to the eighth
embodiment of the present invention. The voltage-to-
current converter comprises an input adder 201, a pair
25   of first stage inverting adders AMP1-1 and AMP-2, and
a pair of second stage inverting adders AMP2-1 and
AMP2-2. The inverting input terminals of the input

adder 201 are connected to input terminals in1 and in2, respectively. The output terminal of the input adder 201 is connected to the inverting input terminals of the first-stage inverting amplifiers AMP-1 and AMP1-2.

5   The non-inverting terminals of the first stage inverting amplifiers AMP2-1 and AMP-2 are connected to the inverting input terminals of the second-stage inverting amplifiers AMP2-1 and AMP2-2, respectively, via internal terminals n1-1 and n1-2. The non-

10   inverting output terminals of the second-stage inverting amplifiers AMP2-1 and AMP2-2 are connected to output terminals out1 and out2, respectively. A capacitor C1 is connected between the inverting input terminal and non-inverting terminal of the second-stage

15   inverting amplifier AMP2-1. A capacitor C2 is connected between the inverting input terminal and non-inverting terminal of the second-stage inverting amplifier AMP2-2.

        In the voltage-to-current converter described

20   above, the signals input to input terminals in1 and in2 are added/inverted by an input adder 201. The resultant signal is then amplified by first-stage inverting amplifiers AMP1-1 and AMP1-2 and second-stage inverting amplifiers AMP2-1 and AMP2-2 respectively

25   arranged for two output terminals out1 and out2.

        When two first-stage inverting amplifiers and two second-stage inverting amplifiers are separately

arranged for the output terminals out1 and out2 as in this embodiment, internal terminals n1-1 and n1-2 do not interfere with each other.   In other words, the internal terminal n1-1 between the first-stage and second-stage inverting amplifiers AMP1-1 and AMP2-1 does not interfere with the internal terminal n1-2 between the first-stage and second-stage inverting amplifiers AMP1-2 and AMP2-2.   As a result, the output variation at the internal terminal n1-1 does not affect the internal terminal n1-2.

If a balanced amplifier is constructed by using a voltage-to-current converter according to this embodiment, influences on differential-mode components can be eliminated even when a phase compensating capacitance C2 is sufficiently increased and sufficient stability is ensured for common-mode components. This makes it possible to realize a stable balanced amplifier.

As each of the input adder 201, the first-stage inverting amplifiers AMP1 and AMP2, and the second-stage inverting amplifiers AMP2-1 and AMP2-2 a common source circuit in which two transistors are connected, at most, in series between power supply lines (between a power supply voltage Vdd and a power supply voltage Vss) as shown in FIG. 10 may be used.

The correspondence between the block diagram of the voltage-to-current converter of FIG. 12 and the

circuit diagram of the voltage-to-current converter of

FIG. 10 will be described. The input adder 201 in

FIG. 12 corresponds to voltage-to-current converters

103 and 104 in FIG. 10. The inverting amplifiers

5   AMP1-1 and AMP1-2 in FIG. 12 corresponds to an

amplifier 105 in FIG. 10, and the inverting amplifiers

AMP2-1 and AMP2-2 in FIG. 12 correspond to the

n-channel transistors M5 and M11. In other words,

the input adder 201 comprises two pairs of transistors

10   M1 and M7 and transistors M2 and M8 and a pair of

transistors M3 and M9. Each of the inverting

amplifiers AMP-1 and AMP1-2 comprises a pair of

transistors M4 and M10 connected in series as shown

in FIG. 10. The inverting amplifier AMP2-2 comprises

15   a pair of transistors M6 and M12 connected in series.

The voltage-to-current converter shown in FIG. 12

can be applied to the balanced amplifier shown in

FIG. 1. That is, this voltage-to-current converter can

be applied to the voltage-to-current converters Gm1 and

20   Gm2 shown in FIG. 1.

As described above, the balanced amplifier of

the present invention comprises voltage-to-current

converters using simple common source amplifiers.

As a consequence, the maximum value of an output

25   signal amplitude becomes larger than that in the

prior art even in low-voltage operation without losing

the common-mode component eliminating ability.

In addition, since a common output voltage can be controlled by using the positive phase input terminal of each voltage-to-current converter used in the balanced amplifier of the present invention, when a filter is formed, the time constant can be easily controlled.